Density fluctuation near the critical points in symmetric nuclear matter

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Introduction

The first-order phase transition in nuclear matter plays a crucial role in the heavy-ion collision experiments. This phase transition is characterized by a critical point (CP) in the temperature-chemical potential (T-μ) plane. The CP, which contains critical temperature (T_c), pressure (P_c), and density (ρ_c), is a crucial quantity in context to the behavior of strong interaction at finite temperature. Although there have been multiple studies concerning the qualitative investigation of CP, it remains one of the least constrained parameter in nuclear matter studies [1].

In recent times, the particle number fluctuation in the heavy-ion collision experiments has opened new possibilities to investigate the strongly interacting matter. The signature of phase transition at low and high density (liquid-gas and chiral phase transition), such as dimensionless skewness and kurtosis, has generated much attention recently. These fluctuations give new insight into the phase transition and also acts as new probes for studying the QCD phase structure. As the chiral (QCD) phase transition and liquid-gas phase transitions in nuclear matter are of the first order, it would be interesting to examine the variation of density fluctuations in the nuclear matter as well. In context to this, we have investigated the density fluctuation in symmetric nuclear matter at low density by employing the temperature-dependent effective relativistic mean-field theory [2].

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Formalism

We define the nuclear matter using the grand canonical partition (GCE) function where pressure plays the role of thermodynamic potential. The interaction between the nucleons is described within the effective relativistic mean field theory (E-RMF). The density fluctuations are then described by the central moments such as $\langle(\Delta N)^2\rangle$, $\langle(\Delta N)^3\rangle$ etc., where $\langle(\Delta N)\rangle \equiv N - \langle N\rangle$. The scaled variance ($\omega[N]$), skewness ($S\sigma$) and kurtosis ($K\sigma^2$) which are size independent measure of fluctuation, are written as [3],

$$\begin{aligned}\omega[N] &= \frac{\langle(\Delta N)^2\rangle}{\langle N\rangle}, S\sigma = \frac{\langle(\Delta N)^3\rangle}{\langle(\Delta N)^2\rangle} \\ K\sigma^2 &= \frac{\langle\langle(\Delta N)^4\rangle - 3\langle(\Delta N)^2\rangle\rangle^2}{\langle(\Delta N)^2\rangle}.\end{aligned} \tag{1}$$

In the GCE, where pressure (P) depends on temperature and chemical potential, the density fluctuation can be represented in the form of dimensionless cumulants as

$$\omega[N] = \frac{k_2}{k_1}, S\sigma = \frac{k_3}{k_2}, K\sigma^2 = \frac{k_4}{k_2}, \tag{2}$$

where

$$k_n = \frac{\partial^n (P/T^4)}{\partial(\mu/T)^n}. \tag{3}$$

Results and Discussions

We use the G3 E-RMF parameter set [4] to study the fluctuation near the critical point in symmetric nuclear matter. The G3 parameter set reproduces the properties of finite nuclei as well as infinite nuclear matter. It also satisfies the relevant constraint on EoS such as incompressibility, symmetry energy, slope parameter, etc., and observational constraints like Flow and Kaon experiment [2].

First of all, we have calculated the phase diagram in the $\mu - T$ plane, which is shown in Fig. 1. The critical point shown by the solid circle is calculated by finding the inflation point in the critical isotherm.

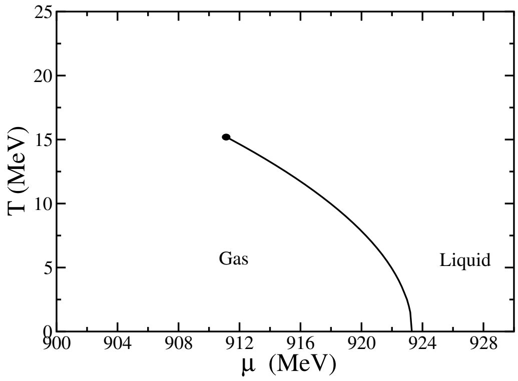

FIG. 1: The phase transition line in the $\mu - T$ plane. The solid circle represents the CP and phase transition line is given by the solid line.

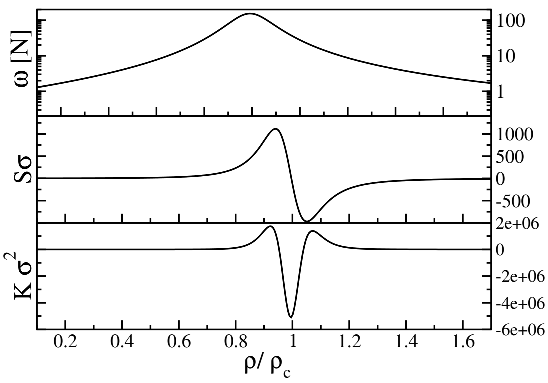

FIG. 2: scaled variance ($\omega[N]$), skewness ($S\sigma$) and kurtosis ($K\sigma^2$) along the critical isotherm.

For every point in the phase transition line for $T < T_c$, we have two solutions with different densities that correspond to the gas and liquid phase at equal pressure. Only a single solution exists for $T > T_c$ that marks the endpoint or critical point. For the G3 parameter set, the critical isotherm is found to be at 15.32 MeV. This value is in agreement with the recently calculated critical temperature by ab initio calculations using the pinhole trace algorithm [5].

Then we study the density fluctuation at 15.32 MeV isotherm to study their behavior near the critical point. For this, in Fig. 2, we show the variation of scaled variance ($\omega[N]$), skewness ($S\sigma$), and kurtosis ($K\sigma^2$) as a function of density along the critical isotherm. The scaled variance ($\omega[N]$) $\to \infty$ at the critical density (ρ_c), and tends to 1 for densities away from ρ_c. Similar to ($\omega[N]$), the skewness and kurtosis diverge at the critical density. Near ρ_c, $S\sigma$ changes its sign when transiting from one phase to other. The negative $S\sigma$ corresponds to the liquid phase, while the positive value of $S\sigma$ represents the gaseous phase.

The kurtosis ($K\sigma^2$) becomes significantly negative ($\to -\infty$) while approaching the critical density and diverges ($\to \infty$) when one move slightly away from ρ_c. This variation in fluctuation near the critical point of liquid-gas phase transition is in harmony with the Non-Gaussian Fluctuations near the QCD Critical Point [6]. The similarity between the liquid-gas and QCD phase transition is also expected from the universality of first-order phase transition.

References

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